The greenhouse gas abatement potential of productivity improving measures applied to cattle systems in a developing region.

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Assessing greenhouse gas abatement potential for low input cattle systems through productivity improving measures

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Short title: Low input cattle system greenhouse gas abatement

Abstract

Developing countries are experiencing an increase in total demand for livestock commodities, as populations and per capita demand increase. Increased production is therefore required to meet this demand and maintain food security. Production increases will lead to proportionate increases in greenhouse gas **(GHG)** emissions unless this is offset by reductions in the emissions intensity **(Ei)** (i.e. the amount of GHG emitted per kg of commodity produced) of livestock production. It is therefore important to identify measures that can increase production while reducing emissions intensity cost-effectively. This paper seeks to do this for low input cattle systems in Senegal, West

Africa. Specifically, it identifies a shortlist of mitigation measures that could be applied to these systems and estimates their abatement potential and cost-effectiveness. The abatement potentials are estimated using GLEAM, with input data derived from primary and secondary sources. Marginal abatement cost curves are presented for different herd systems and the limitations and future requirements are discussed. This paper demonstrates the emission intensity of meat and milk from a livestock system in a developing region can be reduced through measures that would also benefit food security, many of which are likely to be cost-beneficial. The ability to make such quantification can assist future sustainable development efforts.

Keywords: greenhouse gases, ruminant, productivity, mitigation, Senegal

Implications

This cost-effectiveness analysis suggests measures that could reduce greenhouse gas emission intensity from varying baselines of a selection of Senegalese cattle systems, while improving the productivity and profitability of systems. The implementation of policies could encourage adoption of these measures, which would provide both private and social benefits.

Introduction

Developing countries are experiencing an increase in total demand for livestock commodities, as populations and per capita demands increase. The increased production, required to meet this demand and maintain food security, will lead to proportionate increases in greenhouse gas **(GHG)** emissions; unless they are offset by reductions in the emission intensity **(Ei)** of livestock production (Gerber *et al.* 2013).

Emission intensity is a measure of the amount of GHG emitted per unit of output, e.g. kg of carbon dioxide equivalent (kgCO_2eq) per kg of milk. Meat and milk produced by cattle in developing countries often have a higher Ei than the same commodities produced in developed countries. A recent study suggested the regional average Ei of milk from Sub Saharan Africa **(SSA)** is around 9 kgCO_2eq per kg milk, compared to 2 kgCO_2eq per kg milk in North America and Western Europe (Opio *et al.* 2013). High Ei often reflects low levels of productivity, e.g. low milk yields, slow growth rates and high mortalities. It is therefore suggested it should be possible to reduce Ei, and increase food availability, by improving productivity (Gerber *et al.* 2013).

Previous studies investigating GHG Ei of SSA cattle systems are frequently based on Intergovernmental Panel on Climate Change **(IPCC)** inventory guidelines (IPCC 2006). However, Ei estimations vary considerably; for example Opio *et al*. (2013) estimate Ei for SSA milk at around 270 kgCO_2eq/kg protein, whilst Weiler *et al.* (2014) and Udo *et al.* (2016) estimate for Kenyan milk 50 kgCO_2eq/kg protein to 60 kgCO_2eq/kg protein (Ei converted to kgCO_2eq/kg protein by author assuming protein content of milk is 3.3%). It is likely that differences in productivity are responsible for this variation, Opio *et al.* (2013) assume milk yields to be less than 500 kg/cow/year, whilst Weiler *et al.* (2014) and Udo *et al.* (2016) assume more than 1 500 kg/cow/year. This variation demonstrates the importance of herd level analysis to improve accuracy of Ei estimations, from which development opportunities can be accurately assessed.

Functional allocation of GHG emissions remains a contentious topic. Weiler *et al.* (2014) and Udo *et al.* (2016) demonstrated Ei decreased by around 20% when changing from allocating to protein only to allocating to a broader range of cattle functions (e.g. protein, finance, insurance, perceived wealth and dowry). Whilst it is important to recognise that cattle in SSA have functions beyond protein production, and some non-market products can be economically quantified using opportunity value (Udo *et al.* 2016); other socio-cultural functions remain a challenge to value (Weiler *et al.* 2014). However, in the context of GHG mitigation, a priority for success is the identification of potential options to improve productivity that both reduces emissions and increase net profits for livestock keepers, who are the key actors in any successful development.

This paper presents a herd level assessment of low input cattle systems in Senegal, with the specific aims of: a) defining ‘baseline’ GHG Ei of produce, b) identifying a set of mitigation measures to apply to the systems, and c) estimating the abatement potential and cost-effectiveness **(CE)** of these measures.

Livestock rearing supports more than a third of the population and contributes to around 4.8% of Senegal’s gross domestic product (Ministère du Commerce 2013). It is also recognised as an opportunity for poverty alleviation, deserving of appropriately applied development policies (Roland-Holst and Otte 2007). Analysis was primarily based on data collected by the International Livestock Research Institute (ILRI) Senegal Dairy Genetics project (https://senegaldairy.wordpress.com/), from 220 cattle keeping households in the Thies and Diourbel regions of Senegal. Situated in the peanut agro-ecological zone this region is semi-arid with an average rainfall of 400 mm in short wet season (July to October). Cattle are reared for milk and meat in agro-pastoral or pastoral systems (Tebug *et al.* 2015).

Households were categorised depending on: a) the dominant breed type kept (Table 1), and b) the level of management input (defined as either poorer or better, and based on a households average test-day milk yield being above or below the average for the respective breed group (Marshall *et al.* 2016)).

<*Insert Table 1 here*>

Methods

<*Insert Figure 1 here*>

Figure 1 illustrates the method steps followed; the specific steps are described in the following sections.

A. Model 'baseline' systems to calculate emission intensity for protein

An Excel version of the Food and Agriculture Organization of the United Nations' **(FAO)** Global Livestock Environment and Assessment Model **(GLEAM)** (http://www.fao.org/gleam/en/) was used to calculate 'baseline' system GHG Ei for meat and milk production. The system boundary is cradle to farm-gate, and emission categories included are detailed on page 13 of Opio *et al.* (2013). Ei was calculated for protein output (milk and meat); other functions of cattle in these systems are not included in GHG allocation due to difficulties in accurately quantifying them. Input data and sources used for modelling are detailed in Supplementary Table S1.

A sensitivity analysis for the Ei result was carried out by altering each model parameter that could be changed when 'baseline' systems are altered to demonstrate the application of mitigation measures by +10% and -10%. The results of this analysis are presented in Supplementary Figures S2 to S8.

B. Mitigation measure shortlisting process

Mitigation measures were shortlisted through three stages (which are further detailed in Supplementary Table S9). The process began with a review of literature to consider options for cattle production systems to improve productivity and reduce Ei. Measures were included based on options that: a) avoided high costs, b) improved system productivity, c) maintained or reduced absolute emissions, and d) had evidence of feasibility for application in SSA. Inevitably, there was a bias towards shortlisting mitigation measures that could have their application modelled. Secondly, consultation with experts with experience working in animal nutrition, genetics and health management in SSA, removed further measures and saw the addition of others, based largely on feasibility and effectiveness. A final stage of shortlisting involved focus group discussions with study livestock keepers (Salmon *et al.* 2016); this further shortlisted based on likelihood of uptake.

The shortlist of mitigation measures is summarised in Table 2. Feed related measures are dominant due to: a) focus group discussions identifying feed interventions as having the greatest immediate feasibility; and b) the low nutritional value of ‘baseline’ rations, and the availability of higher nutritional value feed materials.

<Insert Table 2 here>

C. Defining parameter changes to model application of shortlisted mitigation measures

‘Baseline’ systems had model input parameters for GLEAM altered to represent the expected changes to the system when each mitigation measure is applied; these are detailed in Table 3. Specific parameter changes were based on available relevant literature. In the first instance measures were applied stand-alone, i.e. assuming no interaction and comparison always to the ‘baseline’ systems. Following an assessment of the CE of measures with no interaction, they were then applied as packages with interactions between them considered. Abatement potential (tonnes of CO_2eq abated per herd, per year) was calculated by multiplying the difference in Ei between ‘baseline’ and ‘mitigation measure applied’ systems by the ‘baseline’ system protein yield.

<*Insert Table 3 here*>

D. Economic analysis and cost-effectiveness

Economic analysis and CE results were based on a typical herd with eight breeding cows, on an annual basis. The CE of each mitigation measure was calculated by dividing the cost of implementing the mitigation measure by the change in Ei (see below equation). Only the private costs of implementation were considered (Note: the cost of tsetse removal, to remove the burden of trypanosomiasis **(Tryps)**, was covered by the government, but included at herd level); social costs (e.g. economic welfare, environmental impacts beyond GHGs, human health and animal welfare) would require further quantification to be included. The cost of implementing each mitigation measure is the change in herd gross margin arising from the implementation of the measure.

$$\begin{matrix} CE \\ (\$/tCO_2eq) \end{matrix} = \frac{Gross\ margin\ with\ measure\ applied - \ Gross\ margin\ without\ measure\ applied}{(Ei\ without\ measure - Ei\ with\ measure) \times Baseline\ protein\ yield}$$

Cost assumptions

Revenue and cost assumptions are detailed in the Supplementary Table S10. The cost of implementing feed mitigation measures represents an annual reoccurring cost to maintain an improved ration. It was assumed that no additional fixed costs or capital investments are required to improve rations and that any additional costs are included in the price of the feed materials. The cost of implementing measures to remove the burden of foot and mouth disease **(FMD)** and lumpy skin disease **(LSD)** also represent an annual reoccurring cost, with control based on the implementation of effective vaccination. It was assumed that any additional costs are included in the price of the treatment. The costs of Tryps burden removal were based on a project within Senegal to remove the tsetse fly vector (Bouyer *et al.* 2014). Due to the isolation of the tsetse population in Senegal from the rest of the African tsetse belt, an assumption was made that once the initial project cost of eradicating the tsetse is applied, the eradication will be sustainable without additional costs. Therefore, to consider net present value, the costs and benefits of the tsetse vector eradication were discounted. A discount rate of 10%, suggested by Shaw *et al.* (2013) to be acceptable for livestock projects, was applied over 30 years.

Results

<*Insert Figure 2 here*>

<*Insert Table 4 here*>

'Baseline' emission intensity of produce

The Ei for protein, emission categories and protein yields for ‘baseline’ systems are illustrated in Figure 2. Key emission categories are enteric methane, feed nitrous oxide (largely from organic nitrogen in urine and manure both deposited directly by animals whilst grazing and collected then spread), and carbon dioxide from energy use in the production of groundnut meal and compound feed. Figure 2 shows the variation in Ei between ‘baseline’ systems and suggests a relationship to productivity (protein yield). The sensitivity analysis (Supplementary Figures S2 to S8) revealed that the Ei result is most affected by the ration digestibility, milk yield, body weight and fertility rate; therefore the ‘baseline’ values for these parameters are presented in Table 4.

<*Insert Table 5 here*>

Mitigation measure abatement potential and cost-effectiveness

The CE and GHG abatement potential of the shortlisted mitigation measures applied to typical herds (with eight adult females) of the ‘baseline’ systems are detailed numerically in Table 5. An example marginal abatement cost curve **(MACC)** for the indigenous zebu x taurine cross (IZ x BT) better management herds is shown in Figure 3 (MACCs for other systems are shown in Supplementary Figures S11 to S16); this system is chosen as an example as at ‘baseline’ it shows greatest productivity (Figure 2) and provides the highest household profit (Marshall *et al*. 2016). The MACC indicates: a) the CE of emission abatement (y-axis), b) the GHG abatement potential for each measure (x-axis), and c) the total cost of each measure (the area of each bar). The MACC displays a reference line to show a shadow price of carbon of \$31/tCO_2eq, representing the economic cost to society caused by an additional ton of carbon dioxide emitted. Each

MACC suggests measures which are: a) ”win-win”, with potential to abate emissions and provide a private benefit (below the x-axis), b) economically efficient, with potential to abate emissions at a cost less than the social cost of carbon reference line (above the x-axis, but below the reference line), and c) economically inefficient, with potential to abate emissions, but with a cost per tonne of carbon currently greater than the social cost of carbon reference line (above both the x-axis and the reference line).

<*Insert Figure 3 here*>

Discussion

‘Baseline’ emission intensity

The Ei results for milk production (4 kgCO_2eq/kg to 13 kgCO_2eq/kg) (Table 4) are similar to those in Opio *et al.* (2013) (9 kgCO_2eq/kg for SSA), but greater than those in Weiler *et al.* and Udo *et al.* (around 2 kgCO2eq/kg for Kenyan systems). Contrast with Weiler *et al.* (2014) and Udo *et al.* (2016) is likely due to differences in levels of productivity. Specifically in relation to the milk yields for the lower producing Senegal systems (Weiler *et al.* (2014) and Udo *et al.* (2016) consider yields from 1 500 to >3 000 kg/cow/year); and herd structure for all systems, with productive cows making up 30% to 40% of Senegal study herds, whilst cows were 45% to 60% of herds in Weiler *et al.* (2014) and Udo *et al.* (2016). The Ei results for meat production (16 kgCO_2eq/kg to 44 kgCO_2eq/kg) (Table 4) are less than Opio *et al.* (2013) (70 kgCO_2eq per kg beef). Contrast here is likely due to Senegal study systems having animals of a greater body weight (adult cows weighed between 294 kg and 433 kg in comparison to 271 kg in Opio *et al.* (2013)), and a higher cow replacement rate (17% to 21% in comparison to 11% in Opio *et al.* (2013)).

The results demonstrate that for the effective assessment of any development or productivity improvement plans the ‘baseline’ should be considered in detail.

Within the Senegalese systems there is substantial variation in Ei of protein produced from ‘baseline’ systems (Figure 2). Indigenous zebu x taurine cross (IZ x BT) and taurine (BT) herds with ‘better’ management have lower Ei (113 kgCO_2eq/kg protein and 111 kgCO_2eq/kg protein, respectively) than other ‘baseline’ systems (averaging 239 kgCO_2eq/kg protein). The sensitivity analysis (Supplementary Figures S2 to S8) demonstrated this variation is likely to be due to productivity (milk yields, body weights, fertility, and age at maturity etc.) and ration digestibility differences. Indigenous zebu x taurine cross (IZ x BT) and taurine (BT) herds with ‘better’ management are fed rations of a higher digestible energy (59 DE% and 62 DE% respectively) compared to other systems (averaging 56 DE%) (Table 4) (DE%: digestible energy expressed as a percentage of gross energy). Indigenous zebu x taurine cross (IZ x BT) and taurine (BT) herds with ‘better’ management also have a higher level of productivity, for instance higher annual milk yields (2 032 kg and 2 197 kg, respectively, compared to other systems averaging 707 kg). Figure 2 shows both ‘better’ managed indigenous zebu (IZ) and indigenous x Guzerat zebu cross (IZ x GZ) herds have Ei lower than ‘poorer’ managed herds with breed groups of likely higher genetic potential for productivity (indigenous x Guzerat zebu cross (IZ x GZ) and indigenous zebu x taurine cross (IZ x BT) respectively) (Table 1). This demonstrates the importance of suitable management, and that breeds of high genetic potential are not always optimal under challenging conditions with limited inputs. Cross bred animals that introduce some productivity potential but retain some of the resilience of indigenous breeds are often more appropriate (Marshall *et al.* 2016).

Key emission categories

Enteric methane and feed nitrous oxide are expected as key emission categories, and consistent with Opio *et al.* (2013). Through their digestive process ruminants produce methane and production is increased when ration digestibility decreases (Gerber *et al.* 2013). Cattle in these systems spend considerable time grazing pasture, depositing organic nitrogen in manure and urine, and any collected manure is stored solid promoting the release of nitrous oxide. Carbon dioxide from feed production is due to the presence of processed feed components (groundnut meal and purchased concentrate compound feeds) in the rations.

Abatement potential and cost-effectiveness

The CE ($ per tonne of CO_2eq abated) and abatement potential (tonnes of CO_2eq abated per herd, per year) of the shortlisted mitigation measures for each of the production systems are presented in Table 5 and Figure 3. The results suggest that across the ‘baseline’ systems there is potential to abate between 4.7 tCO_2eq (indigenous x Guzerat zebu cross (IZ x GZ) herds with ’better’ management) and 6.8 tCO_2eq (taurine (BT) herds) per herd per year through ‘win-win’ measures. This represents a respective reduction of 10% and 13% to annual total herd GHG emissions. Mitigation measures were modelled as packages, applied in order of their CE when applied in isolation. Consequently, interactions between measures are considered and double counting of abatement potential was avoided.

The effective control through vaccination of LSD and FMD, and the removal of Tryps burden through tsetse vector control are consistent ‘win-win’ interventions for the various systems. The cost of additional vaccinations to fully protect herds is assumed to be outweighed by the expected increases in productivity. For example, the assumed burden of 27% and 22% on milk yield for individual cows with LSD and FMD burdens respectively, which translates through prevalence to 2% and 1.5% respective increase for herd average milk yields, will increase herd revenue from milk sales. The cost-effectiveness of LSD and FMD removal, although always below \$0/tCO_2eq, varies between systems depending on the ‘baseline’ milk yields. The higher yielding breed groups (Indigenous zebu x taurine cross (IZ x BT) and taurine (BT) herds) will experience a greater absolute volume increase in milk yield. For instance, the removal of FMD from indigenous zebu herds (IZ) with ‘poorer’ management changes the herd average milk offtake from 323 kg to 328 kg per lactating cow per year (an extra 5kg per cow), whilst for taurine (BT) herds there is a change from 2 197 kg to 2 230 kg (an extra 33 kg per cow). The removal of Tryps burden through the project explained by Bouyer *et al.* (2014), has an initial project cost, but then is followed by reoccurring annual productivity benefits (Table 3), for example a 7% increase in herd milk yields. Discounting these revenue benefits over a period of 30 years still provides a net present value that outweighs the project costs. A further refinement could be to allocate some of the cost to other benefits of removing the tsetse vector, such as expected health and production benefits for other livestock species and a reduction in grazing pressure (Bouyer *et al.* 2014), this may increase the CE further.

The improvement of hay nutritional value by timing the hay harvest for optimal nutritional value is also suggested as a ‘win-win’ option for all systems. The improved nutritional value of the hay improves the overall quality of the ration, and means less volume is required to meet the energy requirements of the cattle, representing a saving. It is assumed that the improved hay will not increase in cost and will not require any additional labour. The cost-effectiveness, although always below \$0/tCO_2eq, varies between systems depending on the proportion of hay in the ration. The indigenous zebu x taurine cross (IZ x BT) and taurine (BT) herds spend more time housed, so hay is a larger proportion of their ration (30% and 18% respectively); therefore this measure is most cost-effective when applied to these systems. Both indigenous zebu x taurine cross (IZ x BT) with ‘better’ management and taurine (BT) herds also have a higher proportion of millet stover in their ration, making the urea treatment of stover a ‘win-win’ measure for these systems only. For all other systems urea treatment of stover has a positive cost; this is generally close to the social cost of carbon, suggesting this maybe economically efficient from a social perspective.

The measures involving the use of groundnut cake or purchased compound feed are suggested to be expensive, both have significant purchase costs. The improvement of rations using these materials greatly improves digestibility, reducing enteric methane emissions and the volume of total ration required to meet the energy demands of cattle. Measures are applied in packages, groundnut cake with a better CE is applied first and has abatement potential of between 1.6 and 2.2 tCO_2eq per herd per year. The subsequent application of purchased compound feed, will also increase digestibility. However, the response of enteric methane emissions decreases with each unit improvement of ration digestibility, therefore following the further package improvements reduces the power of the measure for abatement. For indigenous zebu x taurine cross (IZ x BT) and taurine (BT) herds the increased emissions from the processing of purchased compound feed increase absolute emissions, so would not be applied as part of the package of measures (Table 5). This highlights a limitation of this study and an opportunity for future refinement in that productivity changes are likely following changes in nutrition (Bryan *et al.* 2013) and these are not fully captured in the current approach. This means that the net costs of the feed measures are likely to be overestimated and abatement potential underestimated.

It is encouraging that the results identify that 'win-win' measures are available, these are important for engagement and increased uptake of measures by livestock keepers. However, their presence raises the question as to why 'win-win' measures, such as the removal of FMD and LSD, are not currently adopted. Focus group discussions with over 200 of the study livestock keepers carried out by the authors suggest barriers include: a lack of initial financial means to invest, a lack of regular access to resources, and system characteristics and traditions (Salmon *et al.* 2016).

Conclusion

The results of this study suggest that the emissions intensity of meat and milk from our study systems can be significantly reduced through measures that also maintain or increase protein production. A portion of this emission abatement could be achieved with apparent 'win-win' measures, improving the likelihood of essential engagement with livestock keepers. However, it is suggested that benefits from some of the measures applied to study systems are likely to be underestimated (and the costs overestimated) because the full impacts of the measures on livestock productivity are difficult to quantify. This is particularly true of measures that improve the nutritional value of rations. The use of modelling to identify and quantify cost-effective measures of productivity improvement, as demonstrated by this study, should be an important primary step in effective sustainable development efforts.

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Tables

Table 1 *Breed groups, into which households are categorised based on herd dominant breed*

Breed group	Description		Number of households
IZ	100% Zebu Gobra or Maure	Low productivity, high resilience to local environment	120
IZ x GZ	25% to 50% Guzerat	Guzerat recently introduced from Brazil, improved meat productivity.	40
IZ x BT	25% to 50% Montbeliarde or Holstein – Friesian	Bos Taurus, high milk productivity, low resilience to local environment	46
BT	75% to 100% Montbeliarde or Holstein – Friesian		14

IZ = indigenous zebu; IZ x GZ = indigenous x Guzerat zebu cross; IZ x BT = indigenous zebu x taurine cross; BT = taurine

Table 2 *Details of shortlisted mitigation measures*

MM	MM identification	Further description
Improved ration supplementation with GNC	GNC +5% (Increase GNC by 5%)	High protein feed resource, locally available as an agro-industrial by-product and present in 'baseline' rations at varying levels
Improved ration supplementation with PC	PC 30 / PC 40% (PC altered to 30 or 40% of the ration) PC +5 (Increase PC by 5%)	High energy feed resource, improves utilisation of poor quality roughages, likely to reduce enteric methane and increase animal productivity[1], present in 'baseline' rations at varying levels
Improvement to timing of hay making	Hay	Hay provides a feed resource for when there are shortages. Effective timing of haymaking can maximise protein content and digestibility[1]
Urea treat crop stovers in the ration	Urea treatment	Treating stovers with urea improves digestibility and protein content[1]
Remove LSD burden	LSD	A *capripoxvirus*, symptoms include skin nodules and fever, which limits animal productivity, vaccination possible[2]
Remove FMD burden	FMD	Highly contagious virus, symptoms include fever and vesicular eruptions on feet and mouth, limits animal productivity, vaccination possible[2]
Remove Tryps burden	Tryps	Tsetse fly transmitted parasite, causing substantial reduction to productivity[2], options for control available[3]

MM = mitigation measure; GNC = groundnut cake; PC = purchased compound feed; LSD = lumpy skin disease; FMD = foot and mouth disease; Tryps = trypanosomiasis

[1]See Lukuyu *et al.* (2012)

[2]Blowey and Weaver (2003)

[3]Bouyer *et al.* (2014)

Table 3 *Details of model parameter changes assumed for the application of each mitigation measure. Disease burdens for lumpy skin disease and foot and mouth disease are for infected individuals, whereas trypanosomiasis burdens are for a population*

	Details of model parameter changes									
				DR (%)						
					calves		young and adult years			
MM	Pop %	Milk yield (%)	BW (%)	at birth	female	male	1-2	2-3	3+	FR (%)
LSD	7.1[1]	27.0[2]	17.0[2]	10.0[2]	10.0[2]	10.0[2]	10.0[2]	9.0[2]	9.0[2]	100.0[3]
FMD	6.9[1]	22.0[4]	31.0[4]	9.00[4]	9.00[4]	9.00[4]	6.00[4]	5.0[4]	4.0[4]	100.0[3]
Tryps	na[5]	7.1[5]	1.1[5]	17.3[5]	18.8[5]	15.8[5]	25.0[5]	20.0[5]	28.6[5]	6.0[5]
GNC	The proportion of groundnut cake is altered, other ration components change on a *pro rata* basis									
PC	The proportion of purchased concentrate feed is altered, other ration components change on a pro rata basis									
Hay	Natural pasture varies in nutritional value seasonally, as does the hay harvested. 'Baseline' hay nutritional value is assumed an average, and is improved to the optimum nutritional value of hay. 'Baseline': DE% = 43.6%[6] gN/kg DM = 15.4[6] Optimum: DE% = 46.5%[7] gN/kg/DM = 16.1[7]									
Urea treatment	Urea treatment increases both the digestibility (+29%) and nitrogen content (+126%) of millet stover[8] 'Baseline': DE% = 33.2%[6] gN/kg DM = 9.6[6] Improved: DE% = 42.8%[8] gN/kg/DM = 21.7[8]									

MM = mitigation measure; Pop % = prevalence of disease in population; BW = impact of disease on body weight; DR = impact of disease on death rate; FR = impact of disease on fertility rate; LSD = lumpy skin disease; FMD = foot and mouth disease; Tryps = trypanosomiasis; GNC = groundnut cake; PC = purchased compound feed; DE% = ration digestibility (expressed as percentage of gross energy); gN/kg/DM = grams of nitrogen per kg of dry matter.

[1]See MEPA (2014; 2013)

[2]Derived from: Daher (1994), Abutarbush *et al.* (2015), Ayelet *et al.* (2013), Hailu *et al.* (2015), Gari *et al.* (2011), Salib and Osman (2011)

[3]Assumed if animal had LSD or FMD it would not be fertile, fertility burden equal to respective disease prevalence (Knight-Jones and Rushton 2013; Gari *et al*. 2011)

[4]Dervied from: Bayissa *et al.* (2011), Lyons *et al.* (2015), Rufael *et al.* (2008), Young *et al.* (2013), Şentùrk and Yalçin (2008), Jemberu *et al.* (2014), Onono *et al.* (2013)

[5]data taken from Shaw *et al.* (2006) details burden for a herd/population with trypanosomiasis

[6]See Jarrige (1989)

[7]See Thior (2015)

[8]See Chenost and Kayouli (1997)

Table 4 *Details of parameters identified by the sensitivity analysis to have most influence on emission intensity (Ei) (kgCO2eq/kg product) result*

Breed group	Mgt	Ei milk	Ei meat	DE%	Milk yield (kg/cow/year)	BW (kg)	FR (%)
IZ	poorer	12.9	44.4	55.0	323.4	294.4	57.1
	better	7.0	25.7	56.5	876.9	316.8	63.2
IZ x GZ	poorer	11.6	40.7	55.2	411.0	301.7	54.5
	better	6.1	22.9	55.3	988.8	309.2	70.6
IZ x BT	poorer	6.7	25.6	57.2	937.1	333.3	54.5
	better	3.8	17.5	58.6	2032.1	413.6	70.6
BT	better	4.1	16.3	62.5	2197.8	432.8	63.2

IZ = indigenous zebu; IZ x GZ = indigenous x Guzerat zebu cross; IZ x BT = indigenous zebu x taurine cross; BT = taurine; Mgt = Level of management; DE% = ration digestibility (expressed as percentage of gross energy); BW = adult cow body weight; FR = adult cow fertility rate

Table 5 *Abatement potential (AP) (tCO_2eq/herd/year), percentage reduction to 'baseline' emissions (%), and cost-effectiveness (CE) ($\$/tCO_2eq$) for mitigation measures applied to typical herds with eight cows; '-' represents where measures were not applicable to the respective system or the application increased absolute emissions.*

			Mitigation measure[1]								
Breed group	Mgt	Result	LSD	FMD	Hay	Tryps	Urea treatment	GNC +5%	PC 30%	PC 40%	PC +5%
IZ	poorer	AP	2.2	1.6	0.2	1.3	1.0	1.9	0.6	-	-
		%	4.8	3.7	0.4	2.9	2.1	4.2	1.2	-	-
		CE	-100.2	-113.7	-31.5	-23.6	61.1	248.6	4060.4	-	-
	better	AP	2.0	1.4	0.5	1.2	0.9	1.9	0.3	-	-
		%	4.1	3.0	1.0	2.6	1.9	3.9	0.7	-	-
		CE	-149.0	-175.2	-76.5	-42.9	40.5	258.0	6809.2	-	-
IZ x GZ	poorer	AP	2.0	1.5	0.4	1.2	0.9	1.6	0.5	-	-
		%	5.1	3.8	0.9	3.1	2.2	4.0	1.2	-	-
		CE	-111.4	-130.4	-45.4	-39.8	43.3	199.3	3056.6	-	-
	better	AP	1.6	1.5	0.5	1.1	1.1	2.0	-	-	0.1
		%	3.4	3.2	1.0	2.3	2.2	4.2	-	-	0.3
		CE	-254.7	-232.6	-79.6	-83.1	62.7	378.1	-	-	6439.4
IZ x BT	poorer	AP	1.5	1.5	0.7	1.0	0.6	1.6	-	-0.3	-
		%	3.5	3.4	1.6	2.3	1.3	3.7	-	-0.8	-
		CE	-245.7	-218.3	-82.6	-84.0	34.4	247.2	-	-	-
	better	AP	1.8	1.6	1.6	1.2	0.3	2.2	-	-0.9	-
		%	2.9	2.6	2.6	1.9	0.5	3.5	-	-1.5	-
		CE	-383.7	-360.5	-125.0	-129.3	-16.2	215.4	-	-	-
BT	better	AP	1.4	2.1	0.9	1.1	1.3	1.8	-	-0.1	-
		%	2.4	3.5	1.6	2.0	2.2	3.1	-	-0.2	-
		CE	-300.2	-260.4	-207.0	-142.6	-112.8	51.4	-	-	-

IZ = indigenous zebu; IZ x GZ = indigenous x Guzerat zebu cross; IZ x BT = indigenous zebu x taurine cross; BT = taurine; Mgt = Level of management; LSD = lumpy skin disease; FMD = foot and mouth disease; Tryps = trypanosomiasis; GNC = groundnut cake; PC = purchased compound feed.

[1]See Table 2 and Table 3

Figure captions

Figure 1 *Overview of methodology*

Figure 2 *Emission intensity (kgCO_2eq/kg protein) (bars, left y-axis) and herd protein production (diamonds, right y-axis) by breed group and management level, based on calculations for a typical herd with eight cows.*

Figure 3 *Annual marginal abatement cost curve (MACC) for a typical herd (with eight adult cows), of indigenous zebu x taurine cross breed group with a better level of management. Measures are applied as a package in order from left to right, with interactions between measures considered. The dashed reference line illustrates a social cost of carbon of \$31/tCO2eq. 1 tonne of CO_2eq is equal to approximately 2% of total herd GHG emissions. Measures appear to not be applied in order of cost-effectiveness (CE); however, they are applied as a package from left to right, with the order defined by their CE when modelled in isolation.*

Figure 1

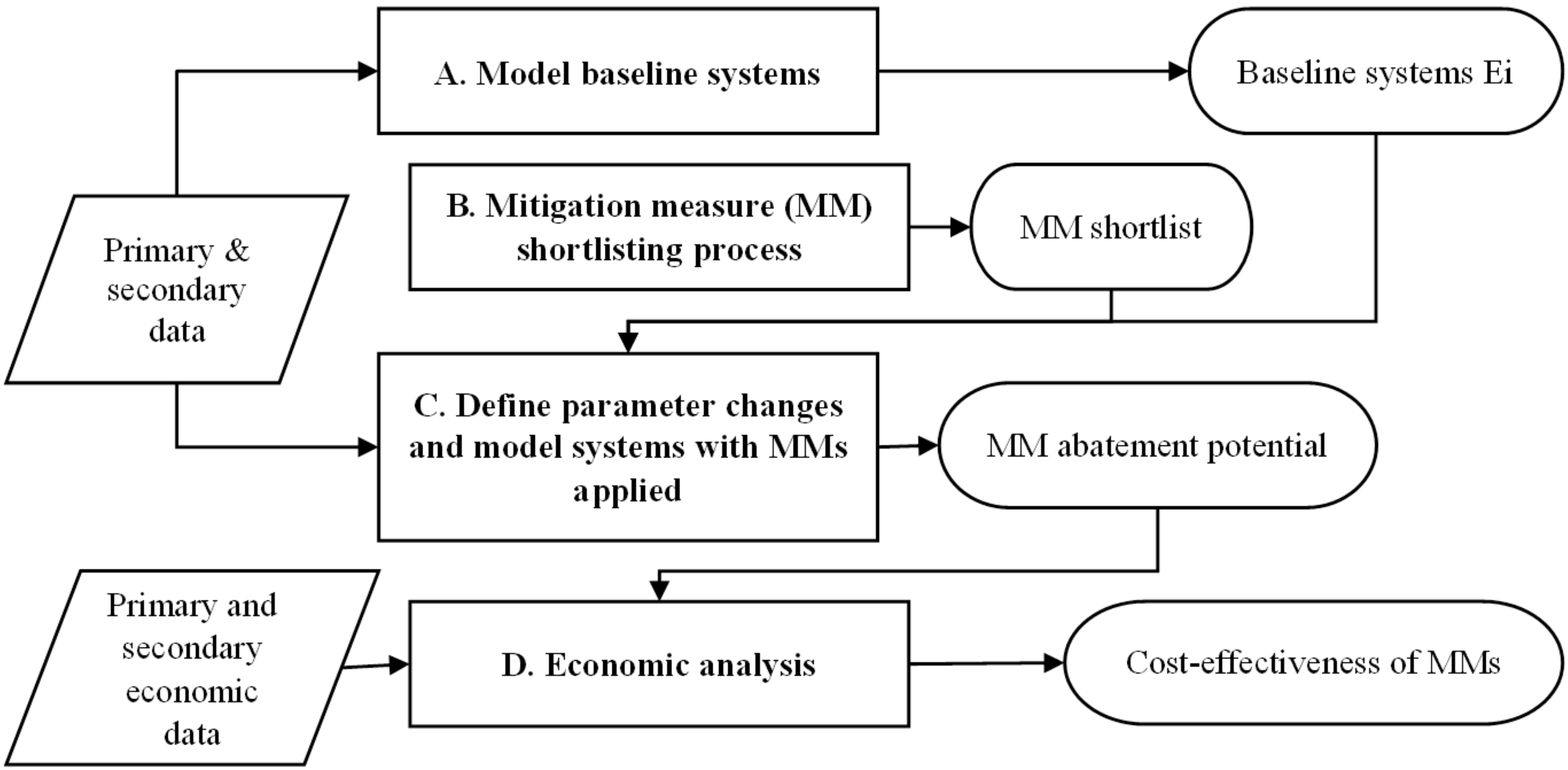

A. Model baseline systems
Baseline systems Ei
B. Mitigation measure (MM) shortlisting process
MM shortlist
Primary & secondary data
C. Define parameter changes and model systems with MMs applied
MM abatement potential
Primary and secondary economic data
D. Economic analysis
Cost-effectiveness of MMs

Figure 2

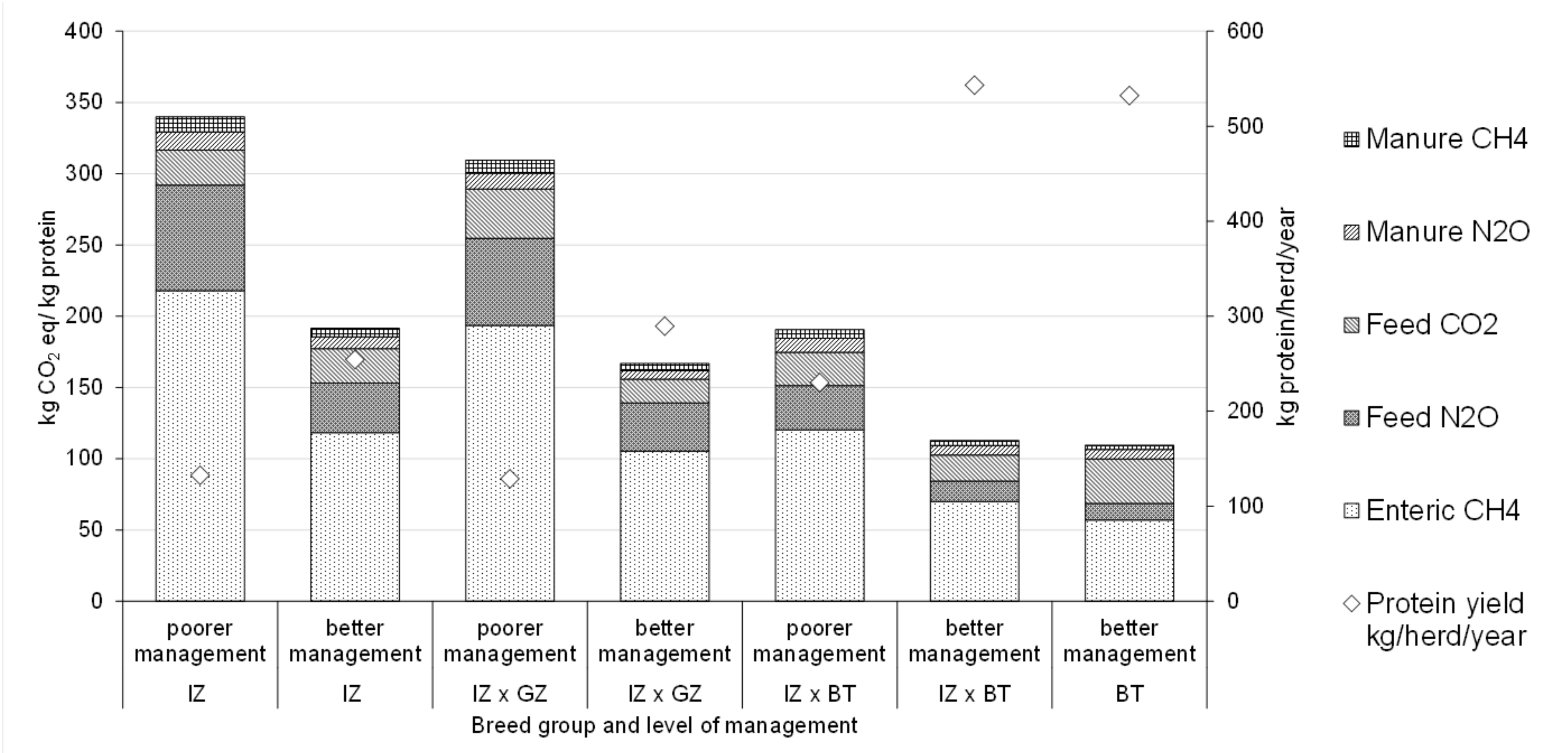
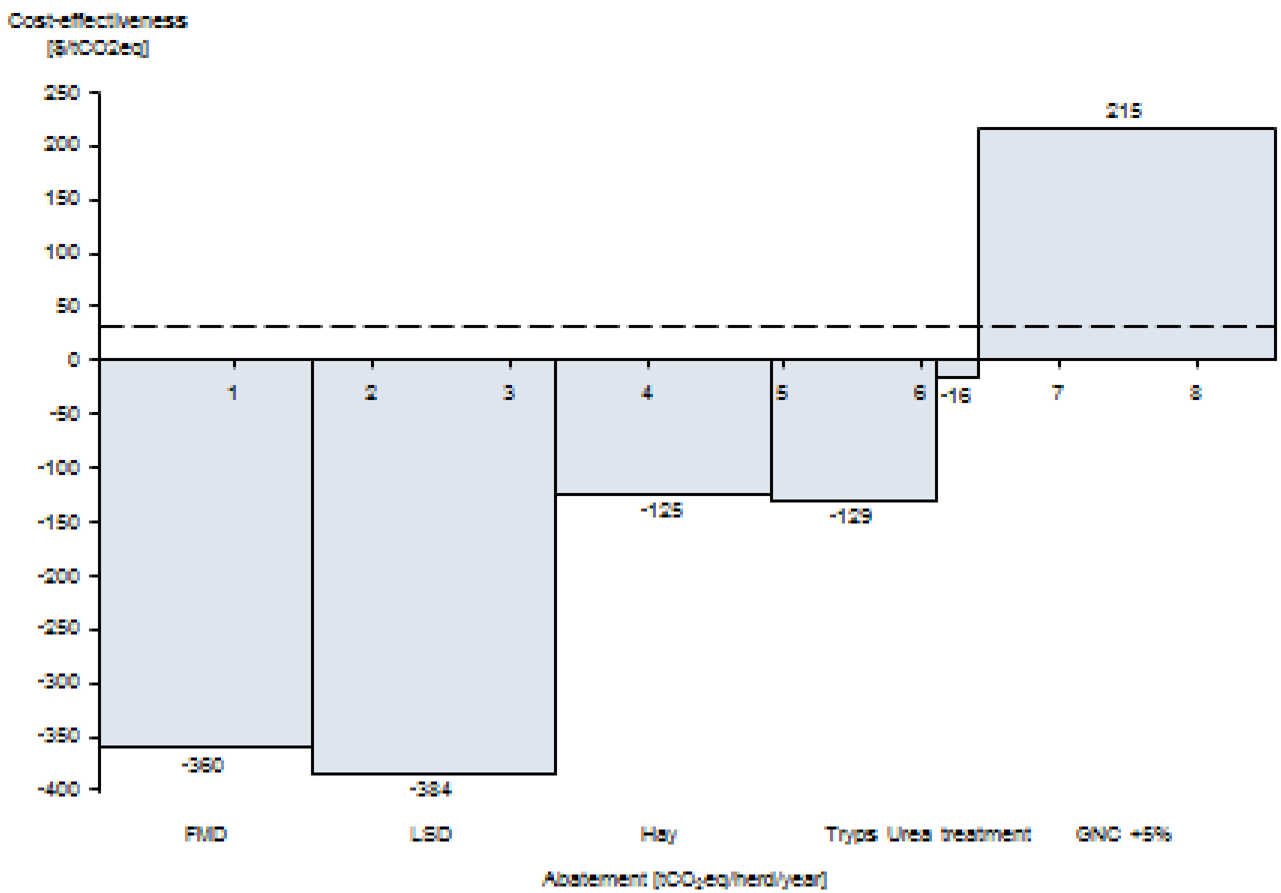

kg CO_2 eq/ kg protein
kg protein/herd/year
400
350
300
250
200
150
100
50
0
600
500
400
300
200
100
0
Manure CH4
Manure N2O
Feed CO2
Feed N2O
Enteric CH4
Protein yield kg/herd/year
poorer management IZ
better management IZ
poorer management IZ x GZ
better management IZ x GZ
poorer management IZ x BT
better management IZ x BT
better management BT
Breed group and level of management

Figure 3



Cost-effectiveness
[$/tCO2eq]
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
1
2
3
4
5
6
7
8
215
-16
-125
-129
-360
-384
FMD
LSD
Hay
Tryps
Urea treatment
GNC +5%
Abatement [tCO2eq/herd/year]